 By John Sienicki, Spectrum Control Inc

FILTERED CONNECTORS ARE LITTLE-UNDERSTOOD BUT USEFUL COMPONENTS FOR REDUCING CONDUCTED AND RADIATED INTERFERENCE. SOME GUIDELINES CAN HELP YOU SPECIFY APPROPRIATE TYPES FOR YOUR APPLICATION.

Design guidelines ease selection of EMI-filtered connectors

You're near the completion of your design, and the unexpected occurs. During qualification testing, your design exhibits a serious malfunction. After countless hours of troubleshooting, you determine that external EMI is making your system fail. You try to combat the problem by applying electromagnetic theory and by sprinkling lots of discrete passive components onto the pc board. This scenario is common, and one that you can often avoid by using EMI-filtered connectors. This design guide can help you to properly specify a filtered connector for your application.

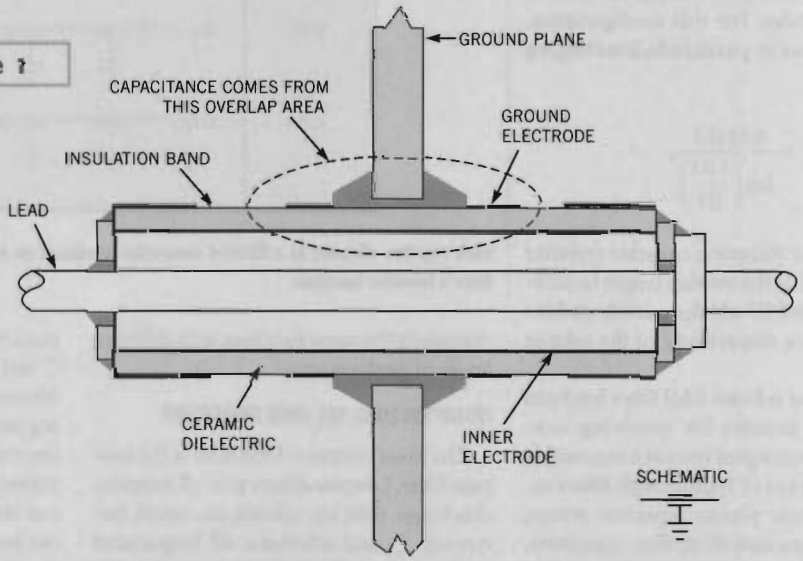
Filtered connectors offer numerous advantages, including far better EMI-filtering performance than equivalent onboard filters, savings in valuable pc-board real estate, savings in costly development time and resources, and reduced time to market. However, these connectors are also the butt of several misconceptions, including that they cost more than onboard filters, are complex, are not durable, and are long-leadtime devices.

Although most of the advantages of using filtered connectors are somewhat intuitive to engineers, some are more difficult to quantify. No simple rule of thumb exists to determine the relationship among cost, complexity, and leadtime for all applications. However, it is important to understand the advantages and limitations of the technology, so that you can make appropriate evaluations for your application. This guide explores the mechanics and performance of filtered connectors that use miniature integrated filtering elements. It then examines a real-life filtering example that illustrates how to select an EMI filter for an application and discusses various operating conditions that affect filter performance.

WHAT'S A FILTERED CONNECTOR?

A filtered connector looks essentially like any other connector, but it contains miniature integrated filtering components that suppress or attenuate unwanted high-frequency conducted noise. The mating requirements for these connectors are identical to those of their nonfiltered counterparts. It's not surprising that the most popular filtered connectors available use the

Figure 1



Tubular ceramic capacitors make up the filter elements in most filtered connectors.

familiar D-subminiature (D-sub) and circular formats. The engagement end of the connector connects to a mating connector. The opposite end of the connector, the termination, typically either solders directly to a pc board using solder-tail leads or connects to an interface cable using solder-cup terminals.

Next to the filtering elements, the ground plane is the most important part of a filtered connector. Its primary purpose is to provide a low-impedance grounding path for the filtering elements to the shell of the connector. The ground plane also prevents the radiated coupling of high-frequency noise from the termination to the engagement ends of the connector, and vice versa. The ground plane essentially acts like an RF fence that prohibits interference from breaking through to the opposite end of the connector. Last but not least is the filtering element itself. These elements are indeed small, because they must fit into the spacing between the contacts of the connector, which can range from a mere 0.050 in. to approximately 0.150 in. These miniature integrated filters comprise capacitive or inductive elements that fit into the shell of the connector.

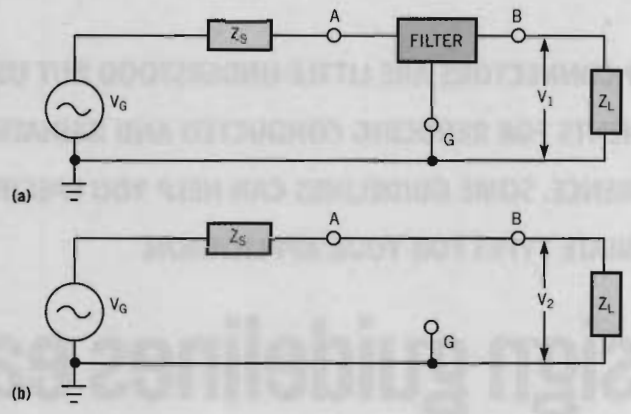
The most popular type of filter element, the "C," or feedthrough filter, is a tubular filter capacitor comprising a tubular length of ceramic dielectric with silver metallization applied to the inside and outside surfaces of the tube (**Figure 1**). Bands of insulating material applied to the outside of the ceramic tube provide separation between electrodes. For this configuration, the capacitance in picofarads, less fringing effects, is

$$C = \frac{0.614KL}{\log\left(\frac{OD}{ID}\right)},$$

where K is the dielectric constant (relative to vacuum), L is the overlap length in inches, and OD and ID are the outside and inside diameters, respectively, of the tube in inches.

This type of tubular EMI filter has been popular for decades for removing conducted noise on signal lines at a reasonable cost. Other types of feedthrough filters include multihole planar-capacitor arrays, chip capacitors, and thick-film capacitors. All these variations have their limitations as well as advantages, but they all perform essentially the same function with different levels of performance.

Figure 2



Insertion loss is the ratio of the power delivered to the load with (a) and without (b) the filter elements in the circuit.

Figure 3

SOURCE IMPEDANCE	CONFIGURATION	LOAD IMPEDANCE	DECIBELS/ DECADE
HIGH		HIGH	≤20
LOW		HIGH	≤40
HIGH		LOW	≤40
HIGH		HIGH	≤60
LOW		LOW	≤60
LOW		HIGH	≤80
HIGH		HIGH	≤100

Each reactive element in a filtered connector produces an additional 20-dB/decade roll-off in the filter's transfer function.

INSERTION LOSS: THE MAIN INGREDIENT

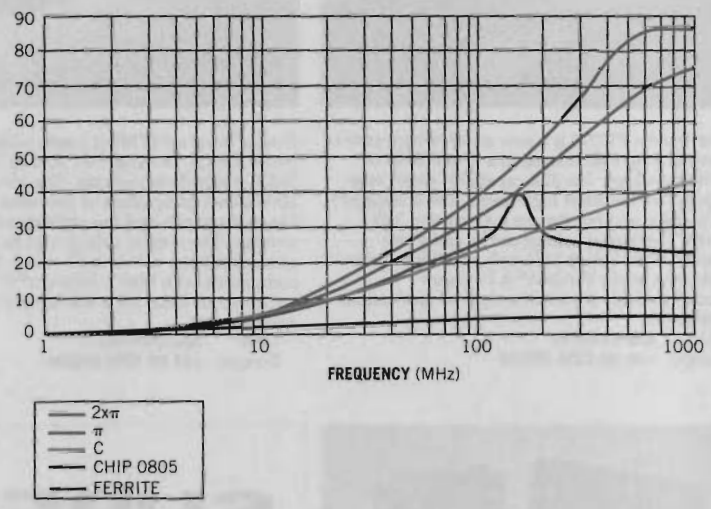
The most common EMI filter is the lowpass filter. Lowpass filters pass all frequencies lower than the corner, or cutoff, frequency, f_C, and attenuate all frequencies greater than f_C. Practical lowpass filters in connectors consist either of a simple capacitive or inductive element or of several C and L elements in cascade for improved filtering performance. You measure filtering performance by determining the filter's insertion loss (IL). IL is the ratio of the power delivered to the load with and without the filter in the circuit. Because power can be a function of either current or voltage, you can also define IL as the ratio of either current or voltage, with voltage the

more popular. You express IL in decibels over a frequency range of interest.

Military Standard 220 describes the method of measuring IL for single-capacitor and multiple-circuit EMI-suppression filters in 50Ω systems at frequencies as high as 1000 MHz. The standard also stipulates that you can test for IL with dc load currents from 0.1 to 20 MHz. According to Mil-Std-220, IL in decibels is $20\log(V_1/V_2)$, where V_1 is the voltage across the load with the filter in the circuit and V_2 is the load voltage with the filter not included (**Figure 2**). In addition, using modern network analyzers, you can readily measure IL using scattering parameters: IL (dB)=$20\log(s_{21})$, where s_{21} is equivalent to the voltage ratio above. Note that, because V_1/V_2 or s_{21} is less than one, IL in decibels is always a negative number. However, many specifications simply use positive numbers to express a filter's IL.

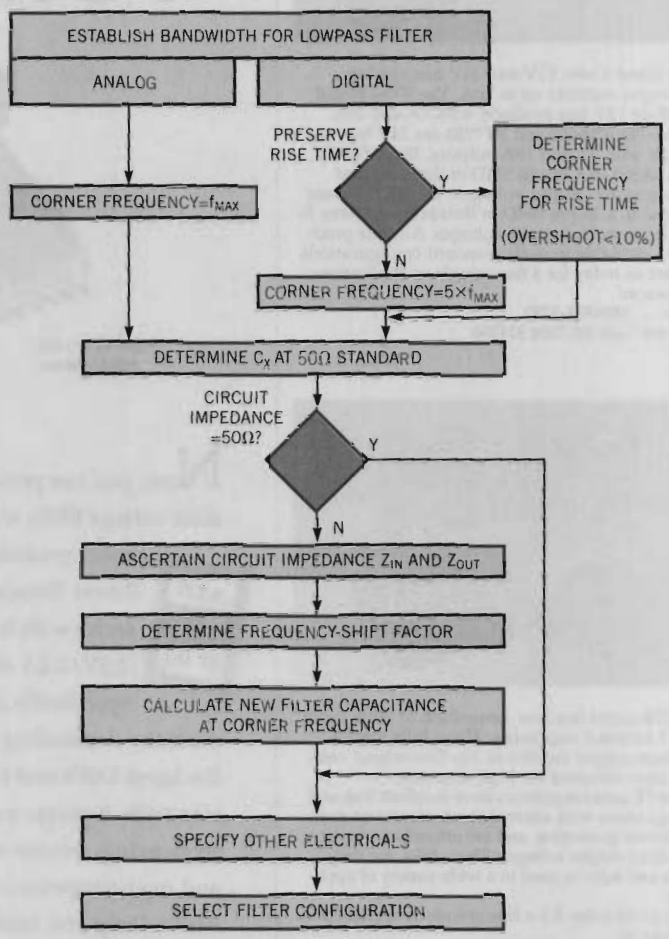
Several popular configurations of lowpass-filter circuits are available in filtered connectors, and different configurations are most appropriate for circuits of different source and load impedances (**Figure 3**). Note that each time you add an element to the circuit, the IL increases by approximately 20 dB/decade of frequency. In reality, the IL-versus-frequency function falls short of the theoretical value, because the capacitors and inductors used in the miniature integrated filter elements are nonideal components. The individual elements' electrical characteristics change with frequency, voltage, and temperature.

Figure 4



A multisection π filter gives the sharpest attenuation; a ferrite element, the least. The 0805 capacitor suffers from self-resonance at a relatively low frequency.

Figure 5



A flow chart provides a systematic method for specifying the appropriate total capacitance in a filtered connector.

PERFORMANCE LEVELS

Table 1 lists the performance characteristics of eight filter types. The list is in order of increasing cost, complexity, and performance, ranging from the simple, inexpensive ferrite filters, to high-performance, multisection lowpass filters. Although multisection filters typically come in standalone boxes, some of the smaller boxes attach to the rear of connectors for EMI filtering in higher current applications. The graph in **Figure 4** further illustrates the performance differences for a 1000-pF filter capacitance for various filter types listed in **Table 1**. Filtering performance for filtered connectors is principally a function of the total capacitance in the filter. Because of the small components in these filters, capacitance is the dominant element. Capacitance provides the means for creating the

simplified graphical tools for specifying EMI filters.

The flow chart in **Figure 5** guides you through how to specify an EMI filter. Step 1 is to determine the bandwidth, or corner frequency, of your lowpass filter. If the filter goes into an analog system, simply choose the corner frequency equal to the maximum signal frequency expected in the system. If the filter is destined to operate in a digital system, you must first determine whether you need to preserve the rise time of the transmitted or received signal. If so, then determine the required corner frequency using $f_C=0.35/t_R$, where f_C is the corner frequency in hertz and t_R is the rise time in seconds. If you do not need to preserve the rise time of the signal, then choose a corner frequency at least four times the maximum signal frequency. A cutoff frequency lower than the above guidelines can result in severe signal attenuation or distortion. Choosing a higher cutoff frequency can result in inadequate filtering at interference frequencies.

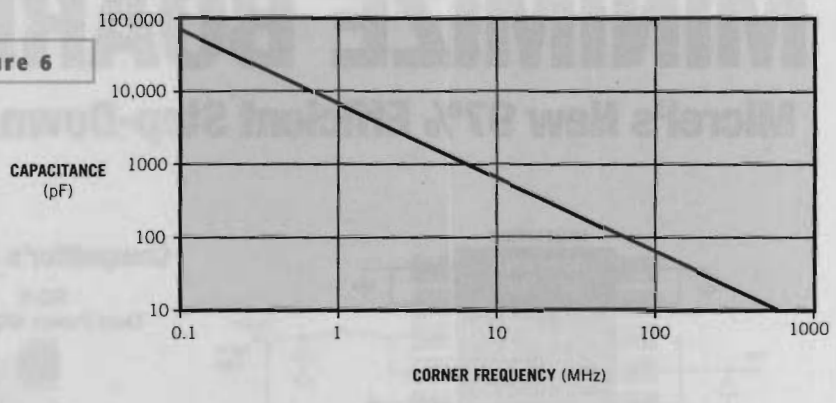
In Step 2, find the total filter capacitance needed in a 50Ω system from the graph in **Figure 6**. If the filter operates in a system using impedances other than 50Ω, you must proceed to the next step. Note that nearly all performance specs available from filter manufacturers apply only to 50Ω systems. All miniature integrated EMI filters with capacitive elements at both the input and output are sensitive to changes in circuit impedances. As circuit impedances increase, the filter's bandwidth decreases, causing unexpected attenuation or distortion of signals in the desired passband. In like manner, the filter's bandwidth increases in lower impedance circuits, allowing more interference to pass through the filter.

Step 3 is to determine the circuit impedances at each end of the filter. The corner frequency for every filter shifts with changing source or load impedances. The corner frequency of an EMI filter can undergo substantial increases or decreases of the design cutoff frequency if you do not account for circuit impedances other than 50Ω. The effect is either insufficient filtering or the loss or distortion of the signal. In some systems, the source and load impedances are complex and can vary dramatically over a range of frequencies. The best and easiest solution for these situations is to obtain an average impedance value about the desired corner frequency. This simple rule of thumb works well for most applications.

Step 4 is to determine the frequency-shift factor. This factor determines the change in filter bandwidth as the ratio of corner frequencies of the filter in a non-50Ω system and the same filter in a 50Ω system. Obtain this factor from the chart in **Figure 7** by calculating or closely approximating the paralleled-impedance value of the source and load impedances.

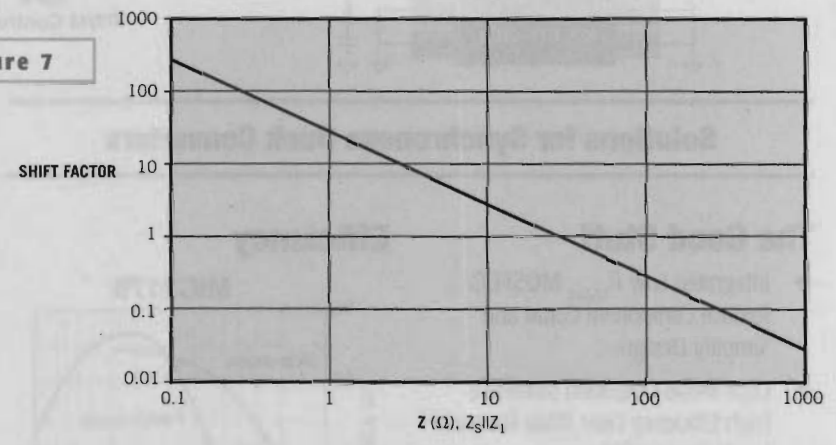
In Step 5, calculate the new filter capacitance needed for the desired corner fre-

Figure 6



Use this chart to quickly determine the capacitance for a given corner frequency in a 50Ω system.

Figure 7



The results of using Figure 6 become invalid for systems using other-than-50Ω impedances. Use this chart to determine a correction factor.

Figure 8



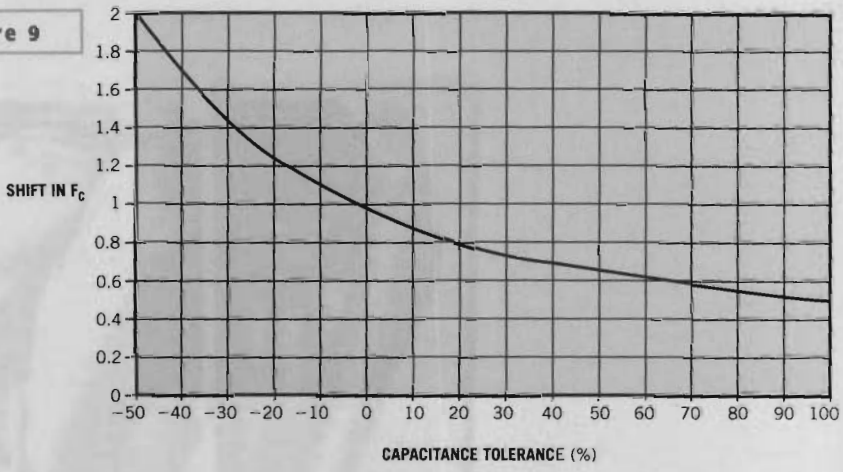
In the example in the text, you want to preserve the 4-nsec rise time in this video signal; the corner frequency of your filter is thus 0.35 ÷ 4 nsec, or 87.5 MHz.

quency by multiplying the capacitance in a 50Ω system by the shift factor. This process adjusts the total filter capacitance so that the filter works properly at your desired corner frequency.

Step 6 is to specify additional mechanical and electrical requirements for the filter. These requirements include connector configuration, type of filter, operating voltage, operating current, insulation resistance, dielectric withstand voltage, operating temperature, connector plating, and environmental issues.

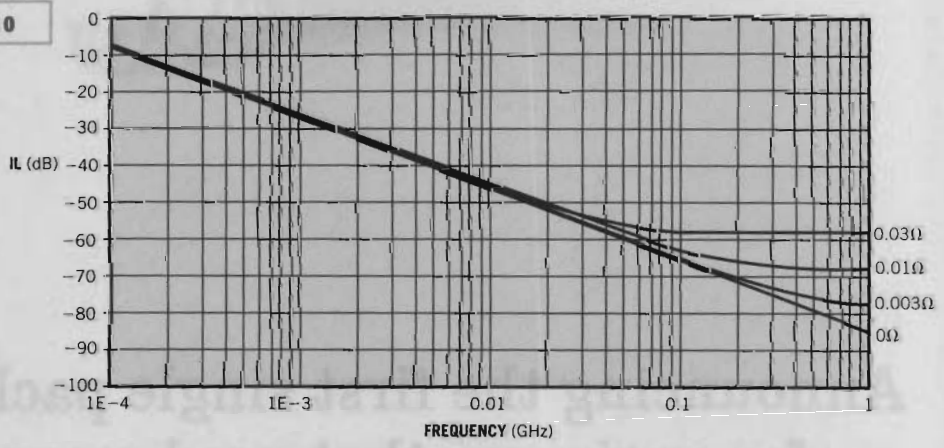
The described selection process works well for feedthrough-type filters at any frequency. It also works well for L, T, or π configurations operating with corner frequencies approaching 30 MHz. At this frequency, the filtering contribution from ferrite elements in these configurations becomes significant. Beyond 30 MHz, the actual cutoff frequency of these filters decreases to less than the desired cutoff frequency of a simple C-type filter. Use caution when you specify miniature integrated EMI-filter designs with corner frequencies greater than 100 MHz. The low component values in these filters increase the likelihood that you'll obtain insertion *gain* rather than insertion loss, especially in systems with mismatched load or source impedances.

Figure 9



Be careful when ordering filtered connectors; sloppy capacitor tolerances can produce wide variations in the corner frequency.

Figure 10



Ground resistance as low as 30 mΩ can cause serious degradation in the attenuation characteristic of a filtered connector.

SPEC'ING A FILTER

The following EMI-filtering challenge illustrates the selection process, in accordance with the flow chart in **Figure 5**. The problem: Radiated emissions in the lower portion of the UHF band are emanating from your video-graphics card. Results from emissions testing show that you need a filter with 10 dB of attenuation at 427 MHz. The cause: VGA pixel-clock frequencies are coupling to RAMDAC circuitry on the pc board and then routing to video line drivers that connect to the outside world via cable connectors. The quick fix: You try filtering with ferrites only to find a marginal 3-dB reduction in emissions. Your next step is to specify a drop-in D-sub ceramic EMI-filtered connector for your video card.

First, establish the bandwidth, or corner frequency (f_C), for the EMI filter. The video output is a variable-pulse-width, digital-data stream (**Figure 8**). You need to preserve the 4-nsec rise time of the signal. The maximum video frequency is 28.5 MHz. Dividing 0.35 by 4 nsec yields 87.5 MHz for the filter bandwidth.

Step 2 is to determine the total filter capacitance required to operate in a 50Ω system for a 87.5-MHz cutoff frequency. From **Figure 6**, the value is approximately 73 pF. However, note that the video card operates in a 75Ω system.

Step 3 is to determine the magnitudes of both the source and load impedances of the circuits connected to the EMI filter. In this example, both are 75Ω and are relatively constant over the frequency range of interest.

In Step 4, use **Figure 7** to determine how far the characteristic IL curve shifts down in frequency if you use it as is. Given the 75Ω source and load impedances, you calculate the parallel combination as 37.5Ω. Using this value, you find that the corner frequency shifts down by a factor of 0.69,

TABLE 1—FILTER PERFORMANCE CHARACTERISTICS

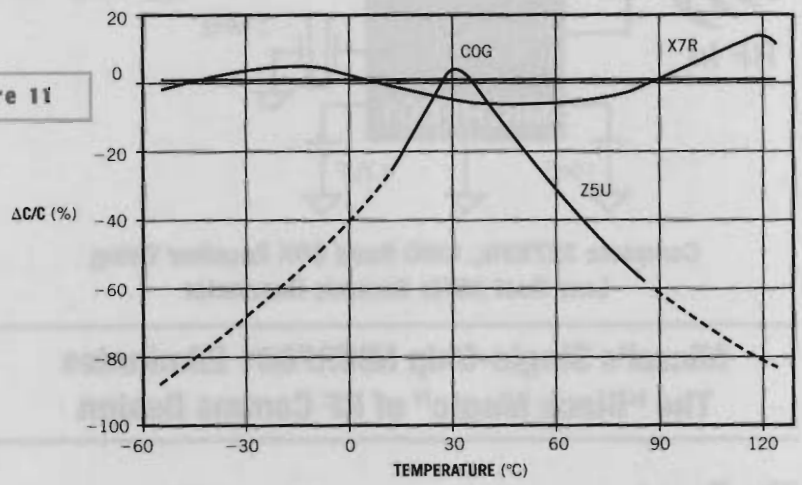
Filter type	IL (s_{21}) (dB) maximum	Slope (dB/decade)	Range (25°C)	Notes
Ferrite, 850μ	6	≤3	NA	No grounding required, no capacitive loading
Chip, 0805	35	≤20	220 pF to 0.1 μF	Limited IL for f >100 MHz, resonates at low frequency
Thick-film C	45	≤20	50 pF to 4 nF	Limited capacitance, limited surge capability
Tubular C	>70	≤20	50 pF to 1 μF	High surge capability, low crosstalk
Tubular π	>70	≤45	100 pF to 12 nF	Medium surge capability, low crosstalk
Planar π	>70	≤45	500 pF to 0.8 μF	Crosstalk problems, balanced capacitance
Multisection	>80	≤60	>50 pF	Large custom package, high current

from 87.5 to 60.4 MHz.

Step 5 is to compensate for the shift in corner frequency by calculating a new filter capacitance for the desired corner frequency. You simply multiply the 73-pF value calculated for a 50Ω system by the 0.69 shift factor you found in Step 3. The new total filter capacitance is approximately 50 pF.

Now that you know the corner frequency and the total filter capacitance, Step 6 is only to determine the other parameters, such as which filter type and configuration to use, voltage and current requirements, and other environmental requirements. You can peruse filtered-connector catalogs or contact a filtered-connector manufacturer to assist you in the selection. For this example, data sheets were available for a 15-pin, high-density D-sub connector that specified IL at greater than 10 dB at the frequency of interest.

Figure 11



Take the temperature characteristics of the ceramic capacitors into account when you specify filtered connectors; the vicious variation of Z5U ceramics, for example, can produce some nasty surprises in the attenuation performance.

VARIOUS CONDITIONS AFFECT IL

Before concluding the selection process, take account of certain operating conditions that affect the performance, or IL, of the connector-housed EMI filter. These conditions include changes in circuit impedance, component tolerance, ground resistance, temperature fluctuations, voltage fluctuations, current fluctuations, frequency fluctuations, and ceramic aging.

A brief review of these conditions may help you to determine their combined effect on filter performance. First, consider circuit impedance. You know that the filter's cutoff frequency depends on the values of both the source and the load impedances. Nonetheless, it's typical for purchasers to buy off-the-shelf filtered connectors without regard for the system impedance. Next, you should consider filter-component tolerances. **Figure 9** shows the cutoff-frequency variations with respect to the tolerance of the capacitance in the filter. Consider the popular "P" tolerance (100, −0%) that's typical in the filter business. A filter using such capacitors could operate with a corner frequency of the design value to one-half the design value. Therefore, you should specify the appropriate capacitance tolerance to produce an acceptable corner-frequency range.

Another factor in filter performance is ground resistance, the resistance of the connection of the shell of the filtered connector to the equipment chassis. The addition of such resistance reduces the effectiveness of the EMI filter. Incidentally, good grounding is more critical for lower frequency filters than for high-frequency filters. **Figure 10** shows how important good grounding is. Just 30 mΩ of ground resistance in a 100-nF filter degrades IL performance by nearly 26 dB at 1 GHz. You rarely see surface conductivity in filter specs, but it's an important parameter. D-sub connectors, for example, are available in formed-steel and metallized-plastic versions. Filtered connectors made with metallized plastic typically exhibit higher resistivities than their metal counterparts. Mounting techniques also affect filter performance. In some applications, for example, gaps are inevitable between the mounting surface and the flange of the connector shell. You should keep such gaps as short as possible relative to the wavelength of the attenuated signal. You can also insert "waved gaskets" to fill the gaps and improve performance.

Temperature variations of the capacitors in filtered connectors are an important factor to consider. **Figure 11** shows the temperature characteristics of the three most popular ceramic formulations: C0G, X7R, and Z5U. C0G (or NP0) is the EIA designation for a capacitor with a ±30-ppm/°C temperature coefficient. C0G capacitors have a low dielectric constant and thus relatively low values, generally restricting their application to frequencies greater than 20

MHz. X7R capacitors exhibit ±15% maximum variation over −55 to +125°C. They usually cover filter applications operating at 0.1 to 30 MHz. Z5U capacitors have the highest dielectric constant and the worst temperature coefficient: 22, −56% over 10 to 85°C. They're usually found in filters whose cutoff frequency is lower than 2 MHz.

Other component parameters that affect filter performance are voltage, current, and frequency sensitivity, as well as capacitor aging. C0G capacitors are insensitive to applied voltage, but X7R and Z5U exhibit marked sensitivity: approximately 30 and 70% reductions in capacitance, respectively, with 100% rated voltage applied, relative to their 0V values. The capacitors are not sensitive to current fluctuations, but the ferrite elements the capacitors work with do exhibit value shifts as a function of current. If you can't find current sensitivity in a filter's data sheet, you should contact the manufacturer for the data. Ceramic capacitors also exhibit value changes with applied frequency. X7R and Z5U capacitors lose 15 and 25% of their value, respectively, at 1 GHz, relative to their value at low frequencies.

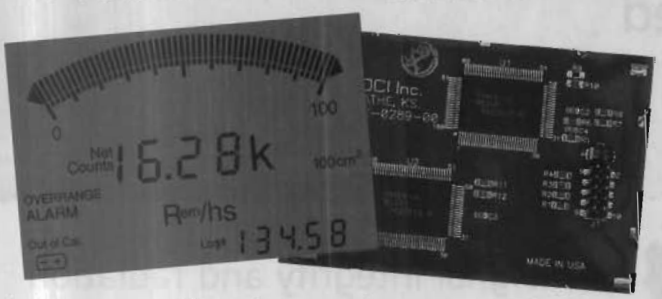
You should also consider ceramic-capacitor aging in your design. Changes in the crystalline structure of barium-titanate-based X7R and Z5U capacitors produce decreases in capacitance value with time. You can determine the value of an X7R or Z5U capacitor at a given time by using $C_F=C_I(1-R\log t)$, where C_F is the final value, C_I is the initial value, R is the aging rate, and t is the elapsed time in hours between measuring C_F and C_I. For X7R capacitors, R is approximately 1.5%/decade-hour; for Z5U, 4.5%/decade-hour. As an example, an X7R capacitor loses approximately 6% of its value in 1000 hours; a Z5U capacitor loses approximately 18% of its initial value in 1000 hours.

To sum up, these graphical techniques and guidelines are appropriate for C, or feedthrough, filters that operate at any frequency. They also work well for miniature L, T, or π filters that operate with corner frequencies as high as 30 MHz. Beyond 30 MHz, the actual cutoff frequency decreases relative to the design frequency because of the impedance contributions of the ferrite elements in the filter configurations. □

AUTHOR'S BIOGRAPHY

John Sienicki manages R&D engineering at Spectrum Control Inc (Erie, PA, www.spectrumcontrol.com), where he has worked for six years. He develops new products and assists product engineers with technical issues on existing products. Sienicki, a registered professional engineer, holds a BSEE from Gannon University (Erie, PA) and an MSEE from Pennsylvania State University (University Park, PA). A member of IEEE, he enjoys ham radio (call K3QJL) and coaching kids' sports activities.

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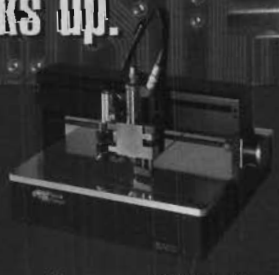
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